METHODS AND APPARATUS FOR CALIBRATING A COLOR DISPLAY

Description

This application claims the benefit of U.S. Provisional Patent Application No.

5   60/195,837, filed April 11, 2000, which is herein incorporated by reference.

Field Of The Invention

The present invention relates to methods for color display calibration which is

especially useful in a network for assuring consistency of color reproduction of multiple

10   color devices. The invention further relates to an apparatus for calibrating a sensor which

may be used for measuring color of a color display in calibration of the display. The

invention is related to U.S. Patent No. 6,043,909 and U.S. Patent Application No.

09/139,498, filed August 25, 1998.

15   ## Background Of The Invention

The calibration of color displays, such as cathode ray tube (CRT) displays, has

conventionally been provided by software in the personal computer coupled to the display

for enabling a user to manually modify characteristics of color displays, or select

predefined color transformation curves. Often, such calibration is a part of typical

20   Desktop Publishing Software. Calibration may be improved by the use of a sensor for

measuring color from a display, which can then enable automatic calibration with or

without user intervention. An example of an automatic calibration system is shown in

FIG. 1. FIG. 1 shows a video display 10 with cowel 11 and sensor 12 as generally

described in U.S. Patent No. 6,043,909 and U.S. Patent Application No. 09/139,498,

25   integrated with a host computer's graphics display section 14 and a display controller for

controlling display 10 function (e.g., brightness, contrast). Sensor 12 is called "lumeter"

in Application No. 09/139,498. Display 10 is shown in cross section as viewed from the

side. An upper, heavy black line may represent a mounting arm coupled to the display

which supports a sensor and may support a cowel. The cowel helps to shield the screen

30   13 of the display from ambient illumination and the sensor enables highly automatic (and

even unattended) calibration. A circumferential cowel provides a "black trap" or surface which prevents any light from reflecting specularly off the screen of the monitor and into the sensor housing - in other words, the lower flange of the cowel provides better shielding from stray light and ensures that the sensor sees only light which is diffusely reflected from the screen. The latter is important to automatic measurement.

Many high performance displays have embedded microprocessors **15** which provides a digital controller for controlling the functions of the display. For example, it is possible to modify the gains in the R, G and B channels by sending signals from the host computer to the processor in the display. In some situations, the sensor **12** communicates directly with the display's processor, rather than, or in addition to, a host computer.

In displays which employ cathode ray tubes (CRTs) the gains in the R, G and B channels affect the voltages on the electron guns and thence the amount of light emitted by phosphors in response to electron bombardment. By adjusting analog gains and offsets, one can exert control over the tone reproduction and neutral balance of the display. When this method of control is available, it is preferred, but it requires knowledge of the control codes, which vary from one make of display monitor to another. The system of FIG. 1 may be adapted to interact with analogous controls in newer "digital displays."

The operation of Graphics Display Section (software and hardware) of the host computer is illustrated in block **14**. Device-independent color image data are fetched from RAM in the host computer and introduced to the graphics display section. The next two steps, namely 1) conversion in a 3X3 matrix (which handles the color mixture problem) and 2) processing of R, G and B data each through its own Look Up Table (LUT) can be combined in a color translator (which may be in International Color Consortium (ICC) or other standard format) for the video display. Channel-separate LUTs can be positioned both before and after the mixing matrix, as detailed in related U.S. Patent no. 6,043,909 and U.S. Patent Application No. 09/139,498. The LUTs may provide a means of influencing neutral balance and tone reproduction. White-balance or neutral-balance is an adjustment to the display system that maps a neutral color represented by numbers in the computer, to a particular displayed color. In other words,

it adjusts the balance between red, green and blue channels of the physical display in order to realize color coordinates of a particular, perceived white. Tone reproduction curves (TRC's) define the orderly progression of relative lightness values for the points in an image. Differently shaped curves mean that neighboring image points will be more or

5   less similar in lightness. Tone reproduction is closely related to a property of displays known as gamma.

Processed data are stored in video RAM and are scanned repeatedly for transfer to the display. The LUTs and the DACs (Digital to Analog Converters) often limit the quality of the system. LUTs are often 8-bits in and 8-bits out, providing resolution that

10   may not be acceptable in some applications. Therefore, although modifications to neutral balance and Tone Reproduction Curves (TRCs) can be effected in the LUTs, it is preferable to make most of the changes in the gains and offsets of the display's RGB channels, if possible, and to reserve the LUTs for "fine tuning."

A generalized node of a Virtual Proofing network as described in U.S. Patent No.

15   6,043,909 and U.S. Patent Application No. 09/139,498 is shown in FIG. 2. A nodal computer 20 receives calibration data (preferably in device independent coordinates which are preferably based on the Standard Observer) from (a) device(s) 22 which can measure a video display 21 and hard copy 23. (One device may be capable of all the necessary measurements or more specialized devices may handle different tasks.) The

20   computer 20 processes the data and 1) modifies shared constituents of the Virtual Proof to be communicated through the network link 25 to other nodes, and 2) exercises appropriate control over the rendering devices (21 and 23) at the node.

Visual calibration may be performed for a display. For example, in U.S. Patent No. 5,638,117, a card or reflector is used in visual calibration of a display. The card is

25   used as a calibration reference by the user with respect to images displayed on the display to enable visual calibration. However, such calibration is not provided for as part of a virtual proof to enable other color devices in a network, which may be remote from each other, to render the same color.

Further, other approaches to assuring calibration of displays provides for locking

30   display controls. For example, a "Color Sentry" feature for locking controls is described

in U.S. Patent No. 5,739,809. However, locking controls do not provide the capability for insuring that the controls are properly set for linear operation of the display.

Summary Of The Invention

5   It is the principal object of the present invention to provide improved methods for calibrating a display to assure that color is consistent between calibrations of the same display and/or between color reproduced by different color displays or rendering devices, such as printers or proofers, which may be in a network.

It is another object of the present invention to provide improved methods by
10   which two display monitors may be placed into a desirable state of tone reproduction by maximizing contrast and setting brightness, such as to 50 or 60%, while insuring that superposition applies.

Briefly described, the method includes providing a color display (or monitor) coupled to a computer system, displaying one or more screens on the display, and
15   adjusting the brightness and contrast of the display to set one or more of white balance, gamma and tone, which accounts for the influence of ambient illumination on color reproduction of display and provides superposition of color of the display.

The color display may have brightness and contrast controls and receive signals from a host computer in a plurality of color channels, such that the method may further
20   include increasing the contrast of the display to about a maximum level for the display, increasing the brightness of the display to about a maximum level for the display, lowering the brightness of the display until superposition of colors is observed, measuring at least the neutral balance and tone reproduction of the display, and adjusting the balance and tone to match desired values.

25   At least one sensor may be directed toward the display for providing color measurement of the display to the computer system. The present invention further provides a system for calibrating such a sensor having one or more channels which is useful for calibrating display surfaces. The system includes one of a self-luminous-display or a reflective surface, a measurement sensor and a reference sensor each directed
30   toward one or more display surfaces, a computer system coupled to the display, and a

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monochromator for illuminating the reflector with light of certain color in which the color

of the light is controllable by the computer system and the measurement and reference

sensors are capable of measuring the color of the reflector when illuminated by the

monochromator to calibrate the measurement sensor in accordance with the

5   measurements taken by both the measurement sensor and the reference sensor.

A method of calibrating color devices associated in a network is further provided

having the steps of adjusting one or more devices to match one or more reference images,

measuring adjusted calibration parameters of the devices, and storing the calibration

parameters for use in calibrating color devices in the network to reproduce substantially

10   the same colors within the capabilities of said devices.

Brief Description of the Drawings

The foregoing objects, features and advantages of the invention will become more

apparent from a reading of the following description in connection with the

15   accompanying drawings, in which:

FIG. 1 is a schematic diagram of a display system showing a color display of a

host computer which has a conventional computer graphics driver to output images from

memory to the color display having a sensor and control for color measurements

described in U.S. Patent No. 6,043,909 and U.S. Patent Application No. 09/134,498;

20   FIG. 2 is a block diagram of a single node of a virtual proofing network described

in U.S. Patent No. 6,043,909 to enable color on different color devices to appear the

same, in which the monitor, nodal computer and colorimeters may represent the display,

host computer and sensor of FIG. 1;

FIG. 3 is a flow diagram of a method by which the sensor of FIG. 1 used for

25   automatic maintenance of calibration is "taught" a white balance adjustment determined

subjectively by the user and by which the preferred white balance can be communicated

to other nodes in the network;

FIG. 4 is a flow diagram of a process for setting up (initializing or resetting

brightness and contrast for linear color mixture) and measuring/adjusting white balance

and tone reproduction of the display of FIG. 1 in the absence of any automatic sensor, i.e., by subjective, visual judgments of the user based on threshold techniques;

FIG. 5 is a top level menu screen of a user interface of a software application operating on the computer of FIG. 1 to enable collection of normative data for subjective calibration by a user which may be used to enable the user to calibrate the display of FIG. 1 visually for carrying out the method of FIG. 4;

FIG. 6 is a screen of the same user interface as FIG. 5 for enabling the user to interact with the software application operating to enable the method of FIG. 4 in which user perception of displayed color is provided in a stimulus configuration that might be used for increment/decrement threshold measurements;

FIGS. 7 and 8 are two screens of the same user interface of FIG. 5 for color matching to reference films placed onto screen to enable subjective, metomeric color matching experiments to verify white balance settings of the display;

FIGS. 9A and 9B are flow diagrams showing a method for obtaining normative reference data for subjective calibration, and using the reference data in calibrating a display, in which the user performs color matching using the screens of FIGS. 7 and 8 to provide white balance;

FIG. 10 is a screen of the same user interface of FIG. 5 for enabling subjectively derived adjustments from the user to tone reproduction;

FIG. 11 is a block diagram of communication by an Internet or WWW (World Wide Web) server with a client computer for virtual proofing on a display coupled to a computer;

FIG. 12 is a flow diagram of a method for operating a color monitor when the color gamut (range of color) is not adequate to display colors on the color monitor;

FIG. 13 is an example of a spectral response of a dual-channel sensor to measure or detect changes in the white point of a known illumination source;

FIG. 14 is an example of a stimulus spectrum of a fluorescent lamp reflected off a white stock in which the lamp is commonly used for appraisal of reflection color images;

FIG. 15 is a block diagram of an apparatus for calibrating a dual channel sensor with a reference device and for verifying accuracy of calibration; and

FIG. 16 is a flow diagram of the calibration operation using the system of FIG. 15.

Detailed Description Of The Invention

Terms used below are described in U.S. Patent No. 6,043,909 and U.S. Patent

5   Application No. 09/139,498, filed August 25, 1998, which are herein incorporated by

reference. The methods described herein for display calibration may be performed using

the common display configuration of FIG. 1 with a host computer. The color display or

monitor may optionally have a digital controller interfaced with the host computer in

addition to the driving signals outputted to the color display. However, any other

10   computer controlled color display may be used with these methods with or without the

sensor and cowel assembly coupled to the display, or the computer being networked as

shown in FIG. 2.

The color sensor may be taught a subjectively preferred neutral balance with the

aid of the user of the computer coupled to the display. The incorporated patent and

15   application describe the color sensor as a spectral one or a colorimeter ("SOM" or means

to simulate the Standard Observer) or a single channel sensor ("lumeter") which sets and

maintains white balance and tone reproduction. Many technologies and particular

products are available that can perform the aforementioned functions.

Although accurate calibration of sensors is essential to reliable network color,

20   practical applications may arise in which an operator uses a calibrated sensor to measure a

white balance established subjectively, so that the information can be shared in Virtual

Proofing as described in the incorporated patent and application. For example, a

"standard" reflection viewing hood for color appraisal of hard copy may exist at a node in

the network. The word "standard" was put in quotes because the deviation of a viewer

25   from its nominal value (e.g. "D50" or Daylight 5000, a standard white value for viewing

printed copy) is often quite noticeable. Non-standard white points constitute a motivation

for subjective adjustment of white balance on a display or other medium. A viewing

hood was described in U.S. Patent Application No. 09/139,498.

It may be desirable to set the white points of displays in the network to the color

30   of paper stock under the illumination provided by the viewing hood. The Users may lack

the means to measure paper white instrumentally or may prefer to rely on a subjective judgment of match. Accordingly, it is one feature of the present invention to provide a User at a node with a viewing hood that provides "standard illumination of reflection copy. User may use a software tool such as Photoshop (Trademark of Adobe Systems) to

5   match the display white to the paper white and invoke a routine in which a sensor measures the balance of primary channels set by the User. This white point information can then be communicated to other nodes through the Virtual Proof and used to modify profiles at the various nodal displays to conform. Use of the information to modify profiles is well known in the art, but will be clarified further in the section entitled "Color

10   Calibration of Displays." A flow diagram of the method is shown as FIG. 3.

First, the User has the option of verifying that the neutral balance and tone reproduction of the physical monitor are consistent with those assumed by the profile-generating software (step 31). User invokes measurement routine to verify that physical gray balance and tone reproduction conform to current profile. For a conventional, three-

15   primary system, there is a relation between neutral balance and the balance of physical activation in the three channels, as described in the next section. The purpose of verifying white balance is to make sure that the display is at a known starting point if the state of calibration of the display has not been checked recently.

The User is instructed to make sure that the reference paper (or other substrate)

20   stock is positioned under the reference illuminator so that comparisons of its color with the display white can be made easily (step 32). User places proofing or printing stock so that it can be compared, under desired illumination, with display screen. Then the software permits the User to modify the white balance at highlight in such a way as to match screen white with the reference (step 33). This may be provided by the user

25   invoking (or executing) a teaching program on the computer coupled to the display which creates on the screen of the display a large window filled with the color of the current system's white point, provides adjustment controls for each of the displays primary channels in a region on the screen, and allows the user to adjust the controls to match screen and the stock visually. Then, the balance of primary channels chosen to match the

30   reference is measured by the sensor **12** coupled to display **10** (step 34) and a white point

is computed for sharing by means of the Virtual Proof (defined in incorporated patent and application) so that color translation profiles for the color devices of the nodes of the network may be revised in accord with the new white (step 35). In this way, the sensor and system are "taught", and may retain, the User's subjective preference. User has the

5   option of verifying that the newly defined white point matches the reference stock and illumination, and reiterating steps 33-35, if needed (step 36).

The foregoing discussion has been in terms of matching a video display to an illuminated white paper. However, colors other than white and devices and media other than video displays and paper, may also be matched in the same manner. For example,

10   information regarding how to match a paper substrate color to a textile's off white color could be prepared for incorporation in a Virtual Proof with reference to this and the other applications cited above.

In the ordinary operation described in incorporated patent and application, the sensor measures the balance of activity in the primary channels, computes the white

15   point, compares the white point to a standard value or to that assumed by the image processing computers of the network and then determines the re-balancing necessary to bring the physical display into conformance. The re-balancing may be implemented by changes to offsets and gains in the analog section of the display controls and/or modifications to LUTs in the graphics control circuitry of the host computer.

20   For some users and applications, a variation of the foregoing scheme, in which complex images are matched rather than homogeneous fields, may be desirable. In this case, there are two ways of utilizing the match data. In one, the sensor measures white point and tone reproduction curves of the monitor after matching and records them, or correction functions based upon them, in the Virtual Proof. In the other, the sensor is

25   used to ensure that the system is in calibration (white point and tone reproduction at least – possibly chromaticities, too.) Then, the User employs color editing tools (gray balance, tonal correction, selective color, etc.) and the corrections are recorded in the color-to-color' table of the Virtual Proof and shared. Color-to-color' tables are disclosed in the above incorporated patent.

One should consider the following factors for successful monitor color calibration of a display, which may be useful for Internet or other networked applications:

1) knowledge of a linear color-mixture matrix for a set of three, additive light primaries such as are found in today's video display technologies (four or more primaries are considered in other, related applications,)

2) set up of the display with regard to properties such as "brightness" and "contrast," so that it truly operates as a linear, additive device,

3) ability to set neutral balance of the physical display to conform closely to information used to make color translation profiles

4) ability to set tone reproduction (gamma) of the physical display to conform to what is assumed by the application software, encoded in the image data and or represented in components of the color translation profiles and

5) means of measuring and computing the effects of factors such as ambient illumination or maximum attainable highlight luminance on device gamuts and of communicating such information among different nodes in a network and of modifying device profiles in order to compensate and ensure the best possible match at different sites.

Illustrative data from real monitors are shown below in Table One, which may provide a basis for calibration methods described herein. First, the emission of light by excited phosphor molecules under electron bombardment is a stereotypical process. The spectral emission functions of Red, Green and Blue channels in two monitors of the same make are believed to be nearly identical. For example, one monitor was used extensively over 4.5 years and the other monitor has had very limited use over the last 1.5 years. I will refer to these two monitors as Type I, one "older" and the other "newer" in subsequent data presentation. For either monitor of Type I, the spectral emission characteristics do not change appreciably in repeated measurements over extended periods of time. Data from a third monitor of different make ("Type II" herein) are also considered.

Although the examples considered here are based on cathode ray tube technology, the methods and instrumentation apply to any video display technology. In the event that the chromaticities of the color channels of a liquid crystal display, for example, are not constant with time, then instrumental means similar to those described in incorporated

patent and application should be used to re-measure the chromaticities at the required

intervals, unless, of course, the change is predictable to within an acceptable tolerance. In

the latter case, a suitable correction function, known to the controlling system, can be

applied. Also, a simple instrument is disclosed in a subsequent section of this application

5   which applies to situations in which spectral changes (that cause the apparent

chromaticity shifts) are stereotyped in nature, but may not occur at predictable times.

Key results of Table One, as they apply to factors 1 through 4 of the calibration

problem, will be abstracted following definition of the following terms: Gamma is the

slope of the function relating log light intensity to log applied voltage. Dynamic Range

10   refers to the ratio of maximum to minimum luminances emitted by the display in a given

operating condition. Max(imum) Luminance is the brightest displayable tonal value, or

highlight.

Color Mixture should be considered in which the term "chromaticity" used below

refers to a color property based on the Standard Observer. The color mixture problem can

15   be summarized by the following equation:

$$
\begin{pmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{pmatrix} \bullet \begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix}
$$

x, y, z chromaticities in color-mixture matrix   *balance vector*   *White Point vector*

At the left is a matrix of chromaticities, x's, y's and z's which summarize the color

mixture properties of the Red, Green and Blue (indicated by subscripts r, g, b) channels of

the display in relative terms. Chromaticities depend on the spectral emission properties

20   of the primary channels.

To setup the display for linear operation, display controls may be used. Brightness

and contrast are two controls available to Users on almost all displays. The icon for the

brightness control is often a shining sun while that for Contrast is often a split circle. On

the Type II monitor, the controls are available as two knobs that provide continuous adjustment. On the older Type I monitor, the controls are typically available as positive and negative, digital push-buttons - i.e., digital means that continuous control is not available. On the newer Type I monitor, software exists to make the controls visible and operable on the display through a graphical user interface featuring slide bar adjustments.

The brightness and contrast controls influence the offsets and gains in the analog section of a CRT display and determine whether the display is operated within its linear range. The two controls adjust how dark the screen is when the host computer sends zero signals to R, G and B channels as well as the maximum brightness realized when R, G and B are full-scale. The host computer, such as a personal computer, can be coupled to each monitor to output images on the monitor.

White balance refers to the vector-inner-product of the color mixture matrix (see preceding equation) and the balance vector which yields the white point. Many white points are available, depending upon the balance among the three color channels R, G, B. In the software system, one of those white points can be picked which associates with a particular vector of balance factors (b's.) An important aspect of good calibration is to make sure that the channels of the physical monitor are balanced consistently with what the software expects. Mentioned earlier, in the previous section, the offset and gain controls of the display and/or graphic LUTs can be modified to that end.

Even when the color mixture properties of a display are invariant, the efficiency of the channels may change with time. Cathode Ray Tubes exhibit "phosphor fatigue" in which the ability to produce light in response to electron bombardment declines over time. Fatigue may occur differently in the different channels. U.S. Patent No. 5,821,917 (and U.S. Patent Nos. 5,512,961, 5,561,459 and 5,978,745) discloses internal monitoring of beam current and adjustment of same over time to compensate for the loss of efficiency.

For gamma and tone reproduction on a color display, typically gamma is treated as a constant by imaging applications. However, it seldom is constant, usually tending to increase in value as the voltage to the electron guns decreases, i.e., at lower light levels. For this reason, there are three rows of gamma values for each monitor in Table One.

The first is called "slope 255 to 223." What this means is that the log of light output for a digital signal from the host computer of 255 (the 8-bit maximum) minus the log of light output for a drive of 223 is divided by log 255 minus log 223 and so on. The column headings represent different settings of the brightness control. For each monitor, contrast

5   was set to the maximum or very near the maximum. Then the brightness was adjusted to 20%, 40%, etc. of maximum. Generally, the numbers correspond to the luminance of the green channel measured at that brightness setting as a percent of the maximum green luminance at the full scale setting.

TABLE ONE

10

	20% Bri	40% Bri	50% Bri	60% Bri	80% Bri	100% Bri
Newer Type I						
slope 255 to 223	2.78	2.50		2.25	2.04	1.85
slope 255 to 159	3.05	2.65		2.33	2.07	1.83
slope 255 to 31				2.69		
PR 700 Lum, 255 Green	21.98	28.17		35.66	44.43	54.34
PR 700 Lum, 255 White	35.92	45.33	50.34	56.49	69.57	81.92
Dynamic Range	>6K:1	>7.5K:1		10K:1	~500:1	~60:1
Type II						
slope 255 to 223	3.88	2.77	2.45	2.27	1.95	1.70
slope 255 to 159	4.66	2.97	2.53	2.31	1.92	1.64
slope 255 to 31		4.43	3.13	2.35		
PR 700 Lum, 255 Green	14.12	27.89	36.71	42.92	57.71	72.57
PR 700 Lum, 255 White	19.88	38.29	48.23	50.04	52.19	53.33
Dynamic Range	>6K:1	>11K:1	7.5K:1	~550:1	~35:1	~13:1
Older Type I						
slope 255 to 223	unavail.,	2.48		2.26	2.01	1.81
slope 255 to 159	beyond	2.64		2.40	1.92	1.71
slope 255 to 31	adjust.			2.54		
PR 700 Lum, 255 Green	limit	22.35		27.20	37.84	45.25
PR 700 Lum, 255 White				42.39		67.78
Dynamic Range	Suitable data not available					

Below the rows of slopes in the table are measurements (made with a PhotoResearch PR 700 spectroradiometer) of Luminance (Y) for Green channel only and

15   then for all three channels together ("white".) In each case the luminance measurement was made at full scale, i.e., either G = 255 or R=G=B=255. The last row contains the ratio of the reading (by the simple sensor, the "Lumeter" detailed in application no. 09/139,498) at 255 (for green) to the reading where all channels were receiving a digital

drive of 0. It is called dynamic range because it expresses the range of tonal values that can be displayed under the given operating conditions. Where a measurement was not or could not be made, the cell is empty.

Using Table One, the following observations may be made.

5 1. Old and newer Type I monitors behave almost identically, except for the reduction in maximum luminance of the older display to about 80% of those of the newer. This is probably the result of "phosphor fatigue" alluded to already.

2. Large dynamic range and high max Luminance are desirable. The best compromise for achieving these, along with approximately constant gamma, occurs at about 60%

10 Brightness (50% for Type II.) At this brightness, the gammas of all three monitors are very similar and the increases in gamma at lower luminances are similarly small.

3. The Type II monitor (a less expensive, lower performance device) suffers a failure of superposition at brightnesses exceeding about 50%. Superposition is a condition of linearity (an essential property for additive color mixture) which is satisfied when the

15 sum of the luminances of Red, Green and Blue channels measured individually equals the luminance of White (all three channels on together.) Superposition failure is apparent from the fact that white luminance barely increases at all at higher brightness settings, even though green luminance increases steadily.

The foregoing results support the conclusion that any two monitors may be placed

20 into a desirable state of tone reproduction by maximizing contrast and setting brightness to 50 or 60%, while insuring that superposition applies. Where an interface between host computer and monitor exists and the codes needed to control things like offsets and gains are known, the settings can be made automatically. In a subsequent section, a method is described by which Users can make the settings on devices such as the Type II device.

25 Also subsequently, methods will be disclosed for measuring and dealing with luminance reductions due to fatigue, such as using Contrast.

Viewing conditions should also be considered. The difference in maximum luminance between the two Type I monitors (practically identical in other respects) would probably show up as a visible difference in color reproduction if the two monitors were

30 perfectly calibrated and set up side-by-side. An example of where this could matter is in

home viewing of a garment of saturated hue at a clothier's World Wide Web site. Apparent saturation varies with luminance level and could influence a buy/return decision. Strictly speaking, phosphor fatigue (and attendant decrease in max luminance) has nothing to do with viewing conditions, but can be one factor which influences

5   perceived color much as does ambient illumination. It also exemplifies a situation in which knowledge of the absolute value of a parameter such as max Luminance can be included in Virtual Proof data and used to improve the extent of match achievable between two or more sites.

If two monitors were put side-by-side, displaying matching images, and then the

10   amount of backlight reflecting off the screen of one of the monitors were somehow increased, the images would no longer match. The reflected light adds with that emitted by the monitor, decreasing the dynamic range and the saturation of colors.

As is explained in the incorporated patent application, a Lumeter can automatically sense the level of ambient backlight, although it cannot distinguish its color

15   temperature. Methods are described herein for estimating the amount of the ambient backlight and its affect on color balance, based on human threshold detection or on instrumental measurements. Methods are also described for estimating the gamma function as well as the absolute levels of light emitted at various contrast or brightness settings or for different digital signals from the host computer. A simple User-Interface is

20   provided below.

Visual calibration may be performed for a display with the assistance of a user using a calibration reference. The methods described herein provide for a more complete calibration than described in U.S. Patent No. 5,638,117, and such calibration is useful in providing data for networking using the Virtual Proof as well as stand-alone operation of

25   the display. Visual calibration is described in connection with FIGS. 4-10.

A step-wise approach to visual calibration is presented which permits the estimation of parameters, which can be used as constituents of the Virtual Proof without any hardware assist. One of these parameters is the absolute luminance of highlight white on a video display. Differences in the absolute luminances prevailing on two video

displays can give rise to differences in the appearance of imagery on two monitors. The differences could detract from Virtual Proofing.

The use of "visual" calibration techniques in the estimation of Virtual Proof parameters is covered in U.S. Patent No. 6,043,909, which recommends the use of a
5   "standard observer meter" or SOM. As is explained in the earlier application, a SOM may be an electronic instrument designed to simulate the color matching behavior of the Standard Observer. The Standard Observer represents the average human with normal color vision. In this application, a particular method is detailed for insuring that a human performing "visual" calibration provides reliable, objective data. Note that visual
10 calibration, by definition, is not automatic. While it may be more laborious, compared to instrumental methods, and possibly more prone to error, the methods are less expensive and available to a broader base of Users.

Referring to FIG. 4, the method for enabling visual calibration of a color display is shown using thresholds. This method is carried out with the assistance of the user
15 interacting with a software application operating on the computer or via the Internet on the computer. First, identifying information about the display-to-be-calibrated is gathered such as locating information about the monitor in a database (step **41**). At step **42**, contrast and brightness (such as controls of the display) are adjusted so as to insure that the display is operated in the range in which linear color mixture applies. Increment or
20 decrement threshold techniques are employed to adjust brightness in the absence of automatic sensing device. For example, if the monitor is known, library data is loaded from the database, such as chromaticities of R, G and B. The display's contrast setting is raised to nearly maximum value. Then, raise display's brightness setting to max and measure decrement threshold from G=255, R=B=O , and lower brightness to 60% by
25 iteratively using green increment threshold. At step **43**, data from red, blue and white increment threshold tests are combined with the green data to test whether the display is in the linear range (for color mixture – see earlier discussion.) If not, brightness is lowered in modest steps until linearity is realized. In other words, red, blue and white increment thresholds are measured in order to test superposition (step 43a). If at that
30 brightness superposition is not present (step 43b), brightness is reduced (step 43c), until

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superposition is achieved and R, G, and B are all then reset to zero (step 43d). At step **44**, threshold measurements are taken by measuring increment threshold in darkened room and normal light. The threshold measurements provide data useable in step **45** to adjust neutral balance at low display light levels and to compensate for, or alert the User to, the

5   effects of ambient illumination conditions. At step 45, the threshold measurements are completed, and a profile for the color calibration is updated, and in the case of a Virtual Proof, the shareable components of Virtual Proof are updated. The user may optionally verify and refine White Point and Tone Reproduction using reference films (step 46). The steps of FIG. 4 are described in more detail below in which visual calibration is

10   facilitated by the use of screens (FIGS. 5-8, 10) provided on the display by the software (application program) operating on the host computer coupled to the display, or provided to the computer via an Internet connection from a web server. For example, the software could be created by a Java applet, downloaded over the Internet to run in a browser, or it could be a stand-alone application. The host computer would have Internet connectability

15   through a modem, or other network interface means, such as a leased line, and the like. Further, FIGS. 9A-9B further describe the process of the software using the screens of FIGS. 7 and 8.

The procedure of FIG. 4 is applicable with an automatic sensor, such as shown in FIG. 1. The sensor, rather than the user observing the screen to detect when superposition

20   is present, is used to detect display output at max brightness (and an established, nearly maximal value of contrast) and then reduce the brightness iteratively until readings from the sensor indicate that the system is observing superposition. For example, a sensor may be used when a new display is initially placed in service or when automatic sensing suggests that brightness and contrast controls have been tampered with.

25   FIG. 5 illustrates a opening (top menu) screen provided to the user. Step One consists of an array of threshold discrimination tasks designed to measure critical parameters without reliance on instruments or reference transparencies as generally described at steps 41-44 in FIG. 4. Step Two presents step 46 of FIG. 4 and involves a color-matching exercise which employs one or more colored transparency films in an

30   effort to verify and refine the white point setting from step one, and a gradation-like

function employing a reference film step wedge for the purpose of verifying and refining tone reproduction curves.

Weber's Law of human visual perception holds that $\Delta I / I$ is a constant. In other words, when a human just barely detects a light signal against a light background, the

5 amount of incremental light needed is proportional to the amount of light in the background. Of course, it is also possible to measure a decrement threshold - the amount of decrease in light level which is just detectable. Call this quantity Δ^-R in the case of the Red channel of the display. A decrement is the only direction we can go when R or G or B is set to 255 digital, or whatever the maximum is. In this description, ΔR will have the

10 same meaning as Δ^+R, for increment threshold. An increment is the only option when R=G=B=0 and we are trying to measure the amount of intrinsic emission from the tube in the absence of digital input (in a darkened room) or to measure the effects of ambient illumination reflecting off the screen and adding to the light emitted by the tube.

The method described herein employs normative data as the basis for translating a

15 User's threshold discrimination into an absolute physical luminance. Normal color vision is essential. In general, a simple screening for color blindness may be desirable. Preferably, it is administered using the video display.

FIG. 6 illustrates another display screen provided to the user (having selected step 1 of the FIG. 5 screen) in which the stimulus configuration is shown for increment or

20 decrement thresholds. In the latter case, the stripes would appear just noticeably darker than the background at threshold, rather than just detectably lighter. In either case, the idea is to adjust the brightness of the stripes until they appear just noticeably brighter or dimmer than the background. When the User clicks the mouse, coupled to the computer, upon one or more radio buttons on the screen, the user is indicating to the computer that

25 "I just see the change", and the computer then records the difference in intensity of stripes from background. This quantity is the increment or decrement threshold difference.

As noted earlier, the size of the difference depends very characteristically on the background level. Therefore, the method refers to the normative data in order to determine what absolute luminances displayed are associated with which digital codes

30 from the host computer. Normative data are collected from one or more human subjects

using the threshold methods described while also measuring luminances (and other relevant variables) of the stimulus configuration with a calibrated instrument. Preparation of normative data is discussed later, in connection with FIGS. 9A-9B.

5 The method includes safeguards against User carelessness and variability. A test trial proceeds as follows: Set the background level as desired and instruct the User to spend a few moments looking at the screen and adapting to its level of illumination. It is assumed that the User has not recently or is not currently viewing a very bright source, such as nearly direct sunlight streaming in a window behind the display. In the latter case, several minutes of adaptation to normal display screen luminance levels may be

10 required for good threshold data. Then either sound a beep or flash a faint ring of light on the screen near where he should be attending and then present the striped increment/decrement stimulus pattern at some luminance level. Move up and down in luminance, asking the User to indicate when the patterns just become visible and/or invisible; in this way, the threshold difference is identified.

15 As a check on reliability, each time the User indicates threshold discriminability, the user is asked to identify the orientation (horizontal, vertical or 45°) and/or the color of the stripes. If the user is not correct, the user may not have been attending to the task properly and additional trials are needed. This kind of reliability check works best when the stimulus is initially invisible and is raised to the threshold level.

20 It is advantageous to oscillate the stripes through a displacement of one-half cycle of the stimulus pattern. It is convenient to use a 1-dimensional, spatial, square wave pattern as the stimulus. A spatial frequency of the pattern of about 5 cycles per degree of visual angle is useful, but the exact frequency is not critical. For further information, see T. N. Cornsweet, <u>Visual Perception</u>, NY: Academic Press, 1970, pp. 475, for a clear and

25 detailed discussion of increment thresholds, spatial and temporal frequencies of visual stimulation and other psychophysical concepts employed in this disclosure. The stripes may be oscillated at about 5-10 Hz.

Quantization may make it impossible to measure the threshold difference with sufficient accuracy. For instance, digital code 223 (of an 8-bit maximum of 255) from the

30 host computer may be indistinguishable from background illumination on the display

while level 224 is very distinguishable. This can be dealt with by treating each stimulus presentation as a succession of frames. If it were desired to present level 223.5, one could do so by presenting 5 frames of 223 and five of 224 during an interval consisting of 10 frames. The interval must be short enough that the eye will integrate the frames

5   temporally. In this way it is possible to increase resolution and measure accurate thresholds and estimates of absolute physical quantities. The stimulus presentation might be implemented with the help of Quick Time (trademark Apple Computer, Inc.) movies or functionally equivalent means.

Before measuring any thresholds, all the gamma-compensation LUTs in the

10   system should be disabled. By setting each channel to full-scale (i.e., a digital drive of 255, or whatever code is maximum) or 85-90% of full-scale (in terms of digital codes from the host) and then measuring the decrement threshold we hope to find out what the absolute luminance is in each of the channels and what the balance among the channels is. FIG. 4, step 42, if the monitor is operating in a range where superposition applies, the

15   knowledge of max Luminance in each of the three channels yields the balance vector of the color mixture matrix equation presented earlier. It is assumed that we already know the chromaticity matrix for any given make of monitor or for a particular device. With this information, the white point, or the change in balance needed to achieve a desired white point, can be calculated. If necessary, iterative threshold discriminations can be

20   made to ensure that the desired white point is achieved.

In order to ensure that a monitor is operating in a range where superposition applies, the operating brightness level of the display is set to about 60% of its maximum. The 60% level is set by instructing the User to lower the Brightness (if manual adjustment is necessary, i.e., if system resources for automatic adjustment are unavailable) until a

25   pre-defined threshold point is reached. This may be faster than an alternative procedure (mentioned in FIG. 4, at step 42) of performing a descending series of iterative threshold discriminations. The brightness adjustment can be made using the Green channel only, although either the Red or the Blue channels could be used.

Measuring the increment threshold when the background is R=G=B=0 (FIG. 4,

30   step 44) can serve two purposes. In a darkened room, it indicates what the balance of the

three channels is in the deep shadows. If the shadows have a neutral balance other than that at highlight, this could be corrected by modifying LUTs in the graphics section or by modifying circuit parameters in the physical display, should the latter be accessible to control from the host. Remeasuring the threshold with room lights at normal working

5   levels provides a way to estimate the amount of ambient backlight reflected off the screen as well as its effect on the monitor's color reproduction. In both cases, results contribute to adjustments to the Virtual Proof (FIG. 4, step 45) and to more accurate network color.

If the User cannot or will not darken the room adequately, the desired information may be estimated by measuring increment thresholds at levels intermediate between

10   highlight and shadow. In effect, this is measuring the gamma or tone reproduction curve of the monitor by the increment threshold technique. Resulting data may be used to project the function into the shadows and thereby estimate the parameters of interest.

The second part of the visual calibration procedure (numeral 46, FIG. 4, labeled "step 2" in FIG. 5) uses transparency materials, such as printed transparent plastic sheets,

15   and visual comparisons by a User to verify results based upon visual thresholds.

Referring to FIGS. 7-8, a method step 46 of FIG. 4 (labeled step 2 of FIG. 5) for estimating color mixture properties of a monitor by color matching for white point verification will be described. FIG. 7 shows an opening screen to setup procedure for a "color matching experiment" for FIG. 8, not unlike those performed in order to define the

20   Standard Observer. An annular piece of colored transparency creates a condition of metamerism between the light emerging through the film and light emerging through the central hole when a visual match is achieved by the observer. Italicized annotations on FIG. 7 provide additional explanation.

The monitor image consists of a central area, whose color can be changed by the

25   User as shown in FIG. 8. The central area is exposed through a hole in a film overlay which covers an outer ring of the monitor display which is illuminated at the full-field white (or at 85 or 90% of digital full field in order to allow "head room." The latter is important since some matches may require more than the "maximum" amount of one or more of the primaries.)

In FIG. 8, two methods available to the User for adjusting the central area to match the ring (white seen through colored film.) In one, circular swatches of color surround the ring. Each swatch shows the current match color shifted slightly in the direction of yellow, green, cyan, etc. The User can click on whatever swatch indicates the

5   direction of color error in the attempted match. The match is changed accordingly. Alternatively, or in addition to the swatch method, the User can operate slide bars to vary the amounts of R, G and B separately or all together in order to match the central disc to the surround.

Once amounts of R, G and B required for a visual match are determined, the

10   values are converted into r,g chromaticity values which are used to predict the x,y chromaticities of the prevailing white point. A simple, linear relationship (representable by a 2X2 matrix) provides a reasonable approximation to the relationship between the pairs of variables - i.e., r,g chromaticities of the monitor and x,y chromaticities of the Standard Observer. However, other empirically-defined functions may be used as

15   accuracy requires.

To clarify the method further: The User in the color matching exercise adjusts the amounts of RGB primaries in the "donut hole" in order to match the donut. The chromaticity coordinate, $r = R / (R+G+B)$, according to the familiar, projective transformation used to define chromaticities in the CIE system. r,g chromaticities

20   estimated (by visual means) and computed as outlined herein, can be used to access, through an experimentally pre-determined functional mapping (normative data), the x,y chromaticities of the prevailing white point.

From these data it is possible to work back to the changes in R, G and B needed to achieve the desired highlight neutral balance. Referring, again, to the color mixture

25   matrix equation presented earlier, the x,y chromaticities of the prevailing white point are known, the primary chromaticities of the monitor type are known or can be assumed and it is possible to compute the prevailing balance vector by conventional matrix calculations. Then the balance changes needed to get to the desired white point can be computed. In the foregoing procedure, it is helpful to have data from threshold work, but

it is not essential. To improve reliability, the color matching experiment may be repeated with film donuts of different colors.

Referring to FIGS. 9A, the pre-determined functional mapping in the preceding paragraph is based on normative data gathered as follows: One or more color-normal

5   observers performs the color-matching experiment described at a variety of white balance adjustments of a monitor. Preferably, the experiments are performed for various monitor types (steps 92-93). The x,y chromaticities (or other relevant variables) corresponding to each balance vector or setting are measured with an accurate colorimeter (step 91). The r,g chromaticities corresponding to the observer's match settings are recorded. These

10 data are used to specify a functional mapping such as the linear 2X2 matrix alluded to above. Any mapping that ensures sufficient accuracy is compatible with the method (step 94). Likewise, other variables derived from the color matching data may be modeled compatibly, according to the method. In other words, to prepare normative color-matching data, each type of monitor instrumentality, such as a sensor, is calibrated (step

15 91). The annulus on screen are set up as shown in FIG. 7, and display stimuli as shown in FIG. 8. For each types of monitor, observer makes the color match to the annulus, and then the color value in R G and B is recorded for the color and associated with measurement recorded from the sensor (step 93). A model relationship is determined by the computer between match values and measurements (step 93), and the model is stored

20 in a database accessible on network or other media (step 94).

Referring to FIG. 9B, we briefly review the method of subjective display set-up and calibration, outlined in FIG. 4, with reference to the normative data. Steps 42 and 43 of FIG. 4 are shown in FIG. 9B. At step 96, a User who wishes to verify the white balance adjustment of her display, subjectively, does so by way of judgments similar to

25 those made by the Observer in normative experiments at step 93 in FIG. 9A. At step 97, User-match data are used to infer the display's white balance data rather than to be fitted to them as in FIG. 9A. At steps 98 and 99, the inferred white balance may be compared to that derived by threshold methods (FIG. 4) or may be used to calculate a desired adjustment to white balance settings. In other words, to use normative data collected in

30 FIG. 9A in subjective calibration provided by the user, the contrast control is set near max

and Brightness control adjusted and the threshold is measured until superposition occurs (step 42-43). The user then makes color matches using one or more film annuli as described in connection with FIGS. 7-8 (step 96), and the computer retrieve the model from database, and plug in color match data to compute prevailing white points (step 97).

5   A new balance vector is established (step 98), and if not verified by the user (step 99), steps 96-99 are repeated.

Thus, given knowledge of the type of monitor, there is information about the phosphor chromaticities and basic color mixture matrix. (If the type is not known, it should be possible to form an educated guess and take steps that will improve color

10   rendering by the display.) In order to make a profile, or color translator, the matrix needs to be adjusted for a particular white balance. In order to do this, the initial white balance must be known. If the threshold methods outlined earlier are successful, then the color matching method outlined in this section may be used to verify or supplement data from thresholds.

15   Referring to FIG. 10, a method for verifying and/or fine tuning tone reproduction will be described to produce very good agreement between two monitors. This may be an additional part of step 46 of FIG. 4 after color matching of FIGS. 7, 8, 9A-9B, are performed. FIG. 10 shows a screen for adjusting tone reproduction without hardware assist. This exercise should follow neutral balancing and does not require a film

20   reference target, although having a reference makes it easier. If a film reference were omitted, the User would have to make subjective judgments of uniformity in the steps of lightness of a gray scale step wedge painted (displayed) on the screen of the display by the host computer in accordance with an application program or software. Although, with patience and some training, humans can arrange a series of samples into steps along an

25   uniform scale, it is not the preferred method. Therefore, the preferred method is to use a film reference.

The configuration and associated functionality are illustrated in FIG. 10. The film reference is suggested by the heavy black rectangle. Within it are 8 patches ranging from fairly dense to very low in density, proceeding from left to right. The area of the film

30   outside the patches should be close to the maximum density. These may be conveniently

manufactured on black & white lith film using a calibrated, linearized half-tone separation film recorder, although a continuous tone target may also be made. The screen ruling of a halftoned image should be such as to minimize moire or beating patterns with the underlying pixel structure of the video display.

5   The target would be affixed to the screen over an area slightly smaller than the film target. That area of the display will be driven to full scale white. The rest of the screen should be left dark, except for an array of 8 neutral patches which should be moveable by the User to butt up to the corresponding gray scale patches of the film target. (The exact number of patches in the scale is not critical and the User can choose to work

10   on selected patches, relying on spline- or Bezier-like techniques to ensure a smooth tonal mapping.) In the bottom right corner of the screen is shown a graphical gradation curve on which each patch of the monitor's gray scale is represented by an "x" or a numerical indicator that correlates with the displayed gray scale. Initially, the x's appear on a line of slope 1, as though the initial tonal transfer characteristic of the monitor were correct.

15   The User can move the x's up or down as needed to match the lightnesses of corresponding steps of the film and monitor gray scales. Corrections indicated by the Users in this process will be used to correct the gains and offsets within the display and/or the LUTs in the graphic display section of the host. Specifically, the corrections made, either channel-by-channel, or on the sum of the channels, in order to match the displayed

20   gray scale to the film gray scale, are recorded by the software and then used according to the well-known algorithm (cf., H. E. Rose, 1955, "Adaptation of electronic color correction to the printing process," TAGA Proceedings, pp. 15-27, published by the Technical Association of the Graphic Arts, Rochester, NY 14623) illustrated in FIG. 30, application no. 09/139,498, to bring the physical display into conformance with what is

25   assumed in the software.

Methods of acquiring the relevant data have been described above to provide calibration data regarding viewing conditions, maximum Luminance levels and like variables, which may be used to optimize Virtual Proofing. Examples of use of the calibration data are reviewed below.

First, maximum luminance is considered. In Table One, two monitors of Type I are observed to differ in the maximum Luminance attainable. Two strategies for dealing with the difference are outlined in this section. The difference can be detected automatically and instrumentally or by using the visual calibration technologies disclosed

5   herein. Either way, the max. luminances at different nodes are stored in a field of the Virtual Proof and compared as part of the preparation for critical viewing.

One strategy calls for reducing the maximum Luminances at other, participating nodes to that prevailing at the node of lowest maximum. This is analogous to the "least common gamut" method mentioned in US Patent No. 6,043,909. It is useful in a

10   situation in which a small number of collaborators (e.g., users at different rendering devices, such as color displays) wish to be confident that they are seeing the same thing (color) and in which the Luminance restriction is not too limiting of color appreciation. Profiles for the different monitors may not have to be modified unless they encode absolute luminances - this is generally not the case. Instrumental and visual methods

15   have been disclosed in this and earlier, pending applications for adjusting down the max. Luminance by the desired amount - visually, they might take the form of a contrast adjustment that is analogous to the brightness adjustment discussed in connection with superposition earlier.

A second strategy employs tonal remappings according to equivalent appearance

20   models such as those discussed by Bartleson and Breneman ("Brightness perception in complex fields," J. Opt. Soc. Amer. 57: 953-957, 1967) and by Holub, et al. ("Color systems calibration for graphic arts. II: Output devices," J. Imaging Technol., 14: 53-60, 1988.) There are many models of color appearance and perceptual constancy that could be used as a basis for calculating profiles for different nodal displays apropos of

25   consistent color. Models of Guth, Hunt, Land, Nayatani and others are well known and many have been applied with varying degrees of success in computer imaging applications. The two studies cited above describe simple adjustments to tonal gradation functions intended to compensate for most of the differences occasioned by different maximum luminance levels.

The kind of approach outlined in the preceding paragraph may be preferred in applications such as e-commerce. A clothier posting images of garments on its web site would want to include information about the assumed Luminance of viewing (or, more generally, about the assumed gamut of a rendering device.) At a particular consumer's

5   node, a browser applet would compare the "recommended" viewing conditions stored and communicated through the Virtual Proof to those prevailing locally and modify at least the tone reproduction aspects of the local monitor profile in order to represent the imagery more consistently with the clothier's intentions. Since the CIE variable of Chroma ("perceived saturation") depends on Luminance, the image-viewing applet might well

10   want to modify the device profile so as to enhance saturation as well.

FIG. 11 expresses the relationship described in the preceding paragraph schematically in which an Internet server 111 provides a web site to which a client computer 112 (or 20 in FIG. 2) can be connected via the Internet or WWW through browser software at the client computer, such as to received GIF Data and Virtual Proof

15   (or data structure) 111. GIF is an image file format that is common in Internet applications. Others, such as JPEG, are possible. At this time, GIF images do not generally have a device independent interpretation; hence, a conversion 113 is shown at the client, and colors modified (via shared and local parts of Virtual Proof) 114 for output via signals 115 to display 116 (or 21 in FIG. 2). It would be preferable if device

20   independent data could be issued from the server or image source.

Next, viewing conditions in terms of the effects of ambient illumination is considered. For example, in the situation in which the consumer is at home and is paying a visit to the clothier's web site. Morning light is streaming in the window and reflecting from the screen into the consumer's eyes. As was mentioned earlier, this reflected

25   ambient light adds to that emitted by the display with potentially dramatic effects on dynamic range and saturation - i.e., on the gamut of the display. In the case in which the effects of ambient illumination are dramatic enough, it may not be possible to make any compensation which will ensure that a garment is displayed with sufficient color accuracy.

The browser applet, on comparing intended gamut with realizable, could either warn the consumer that his color is not credible and/or could use gamut filter technology (gamuts, gamut descriptors expressing models of device gamuts, gamut mapping strategies and gamut filters are discussed in considerable detail in U.S. Patent No.

5   6,043,909) to show the consumer what regions in the image are not faithfully reproduced.

More generally, referring to FIG. 12, given an intended gamut conveyed through a Virtual Proof, available strategies include:

1) If the reproduction gamut at the receiving node is adequate to reproduce all colors faithfully (step 121), then simply display the colors accurately (step 122)

10   2) If the reproduction gamut is not adequate (step 121), then can the gamut be enlarged (step 123)

a) using instrumental or visual calibration technologies to guide the process, do what can be done (increasing Brightness or dynamic range, etc.) to increase the gamut of the device. This could include an advisory to the consumer to mitigate the ambient

15   illumination (step 124)

b) if the deficiencies of gamut at the receiver are not too limiting, and thus the gamut cannot be enlarged (step 123) or do not affect critical colors (such as important garment colors which could be flagged either in a gamut filter or in a special field of the Virtual Proof) then gamut-scaling techniques discussed in the earlier application could be

20   employed to display a sufficiently faithful reproduction if only a little of the gamut is lost (steps 125 and 126)

c) otherwise, warn (notify) the receiver (or user), and use gamut filters to show the consumer which colors are poorly reproduced (step 127). The increase of device gamut of step 124 and scaling of step 126 are not mutually exclusive.

25   To be very clear about how the receiver's display gamut is known: Instrumental and/or visual techniques are employed to obtain calibration data about the device. Calculation of a gamut descriptor (which represents all the colors reproducible with a device) was disclosed in U.S. Patent No. 6,043,909. Briefly, an appropriately white-balanced color mixture matrix and a set of tone reproduction curves are sufficient for

most applications to model a display which demonstrates superposition as explained earlier in this application.

There are various ways of representing the effects of ambient, but one directly incorporates its effects into the primary chromaticities and the tone reproduction curves

5   and, thereby, into the gamut descriptor. Alternatively, colors are often expressed as XYZ TriStimulus Variables (TSVs) in the course of being converted into CIELAB or similar uniform coordinates that may be employed in a gamut descriptor. At the TSV stage, the ambient, expressed as X, Y, Z coordinates may be added to the TSVs generated by the model (without any ambient effects incorporated.) Then the modified model output may

10   be converted into perceptually uniform gamut descriptor coordinates expressive of ambient effects. However, the invention is not limited to the foregoing methods for modeling and incorporating effects of ambient illumination into gamut descriptors and Virtual Proofing data. It is also possible to represent compensations for the effects of differences in max luminance between two devices in terms of a gamut adjustment.

15   Other instrumentation than a single-channel sensor may be used for measuring color of the display screen. It was noted earlier that a single-channel sensor cannot discriminate the exact color of ambient light, only its level. One way of dealing with this is to query the User regarding the source of the environmental light by a software application operating at the host computer coupled to the display. For example,

20   tungsten/incandescent, "cool white" fluorescent, etc. sources have fairly well-known spectral energy distributions which can be used to calculate the chromaticity coordinates of the ambient which is adding to the light emitted from the display. Another way of querying the observer is to employ the psychophysical methods outlined in previous sections. A single-channel device is also unable to detect changes in the chromaticity of

25   one or more of the channels of the display if the spectral energy distribution of said channel changes in shape.

Accurate colorimetry of arbitrary spectral stimuli requires convolution of said stimuli with weighting functions that are linear combinations of the human color matching functions. However, in cases where the stimuli are not arbitrary, but are

30   singular, or few in number, and are known spectrally, it may be possible to use a simple

sensor which does not match human spectral sensitivity. FIG. 13 shows spectral response functions of a dual-channel sensor that is based on a light-to-frequency converter such as that referred to in incorporated U.S. Application Serial No. 09/139,498. The method outlined here is similar to the method outlined in that application for detecting changes in

5   the calibration of a self-calibrating spectral colorimeter.

The spectral response functions chosen for FIG. 13 are arbitrary. In general, it is preferable that they be broad, overlapping and cover, in concert at least, the entire visible spectrum. As shown, they can respond differentially to a change in the spectrum of a stimulus with which they are convolved. More channels than two provide greater ability

10   to localize (by differential changes in the responses of individual channels) exactly where changes in the stimulus spectrum have occurred. In the limit of additional channels, of course, we obtain sampling characteristic of a spectral sensor.

FIG. 14 illustrates a "stimulus spectrum," i.e., that of a fluorescent lamp reflected off a white proofing stock. If changes in that stimulus were predictable, then the dual

15   channel sensor could be calibrated to record chromaticity changes reliably. For example, if the spikes in the spectrum never moved positionally, but fluctuated in relative amplitude, then the dual channel device could predict color changes accurately. The same would be true of other sources, such as video display channels. However, if the spectral changes in the stimulus were more complex and unpredictable, then the dual-

20   channel sensor might be capable only of registering a change in the stimulus over time, indicating a need for re-calibration with a more sophisticated colorimeter.

The situation in which a dual-channel sensor may be preferable to a single channel device is one in which the User does not want to purchase an accurate (expensive) colorimeter but needs to be aware of changes in spectral shape of relevant stimuli, such as

25   a fluorescent source in a viewing hood or a color channel of a video display.

FIG. 15 is a schematic of an apparatus for calibrating a sensor described in foregoing discussion, and FIG. 16 flow-charts the calibration procedure. Sensor **100** is a sensor which is to be calibrated. It is mounted in a fixture so as to view a white reflecting surface of a reflector **107a**, such as upon sheet or board. The reflector can be moved,

30   preferably by an arm that is computer-controlled, in and out of the line of sight of the

sensor in a plane **107**, indicated by a dashed line in FIG. 15. Reflector **107a** may also be

located manually by a user. A reference instrument **104**, whose calibration is stable and

traceable to a standards laboratory such as the U.S. National Institute of Standards and

Technology, also views the same area on the reflector as the sensor to be calibrated. The

5   reference instrument is one whose response at each, narrow wave-band of the visual

spectrum has been measured carefully as part of its calibration. It may be a spectral

instrument, but need not be (FIG. 16, step 162). The goal is to transfer its calibration to

the newly manufactured instrument; its calibration is likely to be more stable over time

than that of the monochromatic source.

10   The monochromator **101** has a lamp assembly **102** to provide white light that is

dispersed into component wavebands. (Edmund Scientific supplies a "mini-chrom"

assembly, which integrates monochromator, lamp and stepping motor, along with

controller software which is adequate for the purposes described here - see p. 222 of

catalogue no. N987A.) A stepper motor **103** is operated by the computer to control the

15   waveband of dispersed light that is focused on the exit slit of the monochromator. Light

emerging from the slit can be shuttered by a shutter **108**, i.e., prevented from reaching the

reflector or allowed to reach it. A lens (or lens assembly) **109** is used to create a fairly

uniform field of monochromatic illumination on the reflector in plane **107**. The sensor-to-

be-calibrated **100** and reference instrument **104** both view the uniformly illuminated field

20   . provided by reflector **107a**.

In the flow chart of FIG. 16, to position sensor 100, the reflecting screen 107a is

lowered, the display 106 darkened, and the shutter of the monochromator 101 is opened

(step 161). The wavelength of illumination is incremented in wavebands such that the

computer causes different, narrow bands of the visible spectrum, from about 380 nm to

25   about 720 nm, to illuminate the field (steps 162 and 163). At each waveband, the

computer measures and records the responses of sensor and reference instrument. These

data are used to determine the spectral response function (plotting response of the sensor

as a function of the wavelength of incident light) of a fully assembled (manufactured)

sensor with reference to the known standard 104 (step 164). Next, the shutter is closed

30   and the reflector 107a is moved out of the way, such as raised so that a video display

screen 106 immediately behind the plane 107 is viewed by sensor 100 and reference instrument 104. The calibration is then verified (steps 165-166) The purpose of this second step is verification of the calibration and quality assurance of the sensor. A sheet of proofing stock illuminated by a fluorescent, viewing illuminator could be used en lieu

5   of the video display. The primaries (primary colors) are each displayed and measured with the sensor and reference instrument, and the expected sensor response is calculated by convolving its spectral sensitivity with the spectral emission of each primary. If the calculated responses equal the measured responses (step 166), the calculation is verified, otherwise, the verification fails and steps 161-165 should be repeated.

10   The following further describes the verification provided at steps 165-166. As a result of prior measurements with a spectral instrument of adequate resolution (see application no. 09/139,498) the computer has stored data on the spectral emission characteristics of each of the primary channels of the display - typically these are called "red," "green" and "blue." However, other primaries are possible. The computer lights

15   up each of the primary channels on the display in turn and measures and records the responses of the sensor-to-be-calibrated and the reference instrument. It calculates the response expected from the sensor using the relation:

$$R = k \sum [e(\lambda) * s(\lambda) \Delta\lambda] \quad (1),$$

where R is the Response of the sensor being calibrated, e is the spectral energy

20   distribution of one of the display's primary channels, s is the spectral response function of the sensor as measured in the preceding step, k is a constant, λ represents wavelength and $\Delta\lambda$ represents the wavelength increment of the summation. Equation (1) can be thought of as a convolution summation with a shift parameter equal to zero.

If it is desired to know the CIE Luminance, Y, that corresponds to R, it may be

25   calculated as

$$Y = k \sum [e(\lambda) * s(\lambda) * \rho(\lambda) \Delta\lambda] \quad (2),$$

where $\rho(\lambda)$ is the ratio of the value of the y-bar color matching function of the CIE Standard Observer to the response of the sensor at each wavelength. Of course, Y can also be calculated directly by its defining equation, but equation (2) shows the

30   relationship to sensor sensitivity.

If the value of R calculated using equation (1) agrees sufficiently well with the value actually measured, the instrument passes quality assurance; otherwise, it fails. In most cases, a recalibration will suffice following an initial failure. Occasionally, an instrument must be discarded.

5   The calibration procedure outlined can be applied to single- or multi-channel sensors. With knowledge of the spectral response of the sensor and of the form and variations of the stimulus, it is possible to calculate changes in the color of the stimulus.

Apparatus and methods have been disclosed for cost-effective and highly accurate set-up, calibration and color-control of video displays.

10   From the foregoing description, it will be apparent that there has been provided improved methods and apparatus for color display calibration. Variations and modifications in the herein described methods and apparatus in accordance with the invention will undoubtedly suggest themselves to those skilled in the art. Accordingly, the foregoing description should be taken as illustrative and not in a limiting sense.

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